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## Effect of the amplitude loading on fatigue crack growth

M. Benachour<sup>a,\*</sup>, A. Hadjoui<sup>a</sup>, M. Benguediab<sup>b</sup>, N. Benachour<sup>a,c</sup><sup>a</sup>LAT, Mechanical Engineering Department, University of Tlemcen, BP 230 - Tlemcen, 13000, Algeria<sup>b</sup>LMPM, Mechanical Engineering Department, University of Sidi Bel Abbas, Sidi Bel Abbas, 22000, Algeria<sup>c</sup>Physics Department, Faculty of Sciences, University of Tlemcen, 13 000, Algeria

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### Abstract

The paper presents an experimental work of fatigue crack growth for aerospace 2024 T351 aluminum alloy under constant amplitude loading. At 10 Hz frequency, the effect of various amplitudes loading is examined for bending V-Charpy specimen. The results of the fatigue tests conducted at  $R=0.1$ , show the effect of the amplitude of loading on the fatigue life and fatigue crack growth rate. The fractography examinations were carried out on scanning electron microscopic SEM and show the presence of fatigue striations in Paris region.

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**Keywords:** Fatigue, crack growth, amplitude loading, aluminum alloy 2024

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### 1. Introduction

The fatigue damage is a phenomenon known since the 19th century and considered that is the most important failure mode to be considered in a mechanical design. Aluminum alloys are the primary material for aircraft structures and that remain the main choice for fuselage. High specific properties and good behaviour fatigue with well known performance characteristics and others advantages represent the main reasons for the continued wide use of aluminum alloys in aircrafts. Aluminum series used are 2xxx, 6xxx, 7xxx and 8xxx enjoy the widest use in aircraft structural applications. The aluminum alloy 2024 alloy under different temper situation is the most widely used alloy in aircraft applications. The aluminum alloy 2024 T351 used in this study, has CFC structure, was studied by many authors [1–3]. Effects of amplitude loading, mean stress and load ratio have been investigated by many researchers.

### Nomenclature

K	stress intensity factor
$\Delta K$	range of stress intensity factor
$b \times w$	section of specimen (thickness $\times$ height)

\* Corresponding author. Tel.: +231 (0) 43 28 56 86; fax: +231 (0) 43 28 56 86.

$P_{\min}, P_{\max}$	minimum/maximum applied load
$\Delta P$	range of applied load
$a$	crack length
$N$	number of cycle
$R$	stress ratio
$C, m$	coefficients of Paris law
$da/dN$	fatigue crack growth rate

The influence of minimum stress and stress amplitude on the fatigue resistance of natural rubber (NR) has been studied by André et al [4]. The experimental results of Abraham et al [5] show that the dynamic fatigue properties of filled elastomers depend on the applied stress amplitude as well as minimum stress. Increasing minimum stresses with constant strain amplitude could increase the service life. For Steel [6], an increase in mean stress cause small increase in fatigue crack growth rate and ratio of stress intensity factor  $U$  characterising the crack closure.

Recently, in Lee et al work [7], the FCGR ( $da/dN$ ) increases and the threshold  $\Delta K_{th}$  decreases with increasing stress ratio  $R$  under constant amplitude loading in different environment (vacuum, air and 1% NaCl solution). The behaviour of short and long cracks under constant amplitude loading conditions were investigated numerically and experimentally by Hammouda et al. [8] when crack tip deformation parameter are used to correlate fatigue crack growth rates. Under constant-amplitude loading, Newman Jr. and Ruschau [9] have shown that the normalised crack opening stress is influenced by the applied stress level for aluminum alloy 2024 T3. The results show that the stress level has a larger influence in plane stress behavior than plane strain. An increasing for the maximum applied load decreases the fatigue life. Experiments have shown that the value of  $R$  influences the crack growth rates. It was argued that the reason for this influence is the crack closure effect. Crack closure was first introduced by Elber [10]. Based on experimental work on aluminium alloy 2024 T351, fatigue crack growth model has been developed by Maymon [11]. It was shown that under constant amplitude loading, the fatigue life is affected by amplitude of loading and stress ratio. Benachour et al [12] have studied load ratio effect on fatigue life of double fillet weld with semi elliptical initial crack for 2024 T351 aluminum alloy. With constant maximum applied load, the mean stress affect the fatigue life. Results have shown an increasing of fatigue life with increasing load ratio.

Constant amplitude fatigue crack propagation data are necessary but not sufficient for a realistic assessment of the resistance of materials to fatigue crack growth. In the present paper, amplitude loading effects on fatigue life and fatigue crack growth are studied. In previous work to account of others parameter, fatigue crack growth under residual stress effects are in preparation.

## 2. Experimental procedure

### 2.1. Material and specimen geometry

The experimentation was performed on the Al 2024 alloy, widely used for aeronautical applications, supplied in the form of 30 mm thick rolled plate. Aluminum 2024 alloy received the T351 thermomechanical treatment (hardened and tempered). This alloy was provided by the ALCAN Company of production of aluminum alloys to the profit of the Centre of Materials, School of Mines Paris, France. The material provided in the form of a rectangular sheet of dimension (745x900x30 mm<sup>3</sup>) is recorded under number 9900055. The chemical composition of different materials used in this study is listed in Table 1. The mechanical properties at room temperature are shown in Table 2.

Table 1: Chemical composition of Al 2024 T351 (wt%)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Ni	Pb	Al
0.105	0.159	3.97	0.449	1.5	0.05	0.109	0.018	0.02	0.056	Bal

Table 2: Mechanical properties of Aluminum alloy 2024 T351

E (GPa)	$\sigma_{0.2}$ (MPa)	UTS (MPa)	A (%)
74	363	477	12.5

Fig. 1(a, b) shows the microstructure of aluminum alloy 2024 T351 respectively in (T-S) and (L-S) orientations. L is rolling direction; T and S are respectively the long and short transversal directions. This microstructure is obtained by polarized light microscopy. The specimen underwent a polishing up to 10  $\mu\text{m}$  followed by an electrolytic attack for one minute duration. The microstructure shows that the size of the grains is significant, which will influence the fatigue behavior.

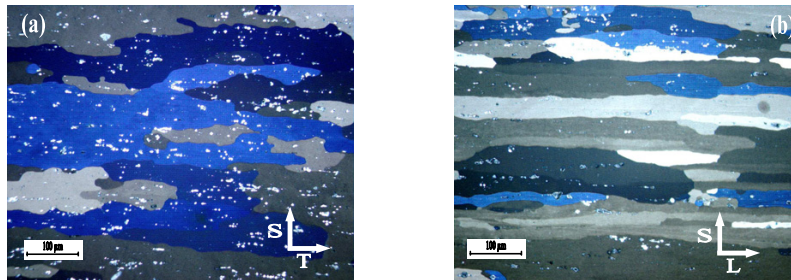


Fig. 1. Microstructure of aluminium alloy 2024 T 351, (a) T-S direction; (b) L-S direction

The specimens V-notch with 45° angle in four bending test are shown in Fig. 2. The specimens are polished to 10 $\mu\text{m}$  finish on the surfaces crack growth. Specimens have ( $b \times w = 10 \times 10 \text{ mm}^2$ ) section with an initial length  $a_0$  for the notch.

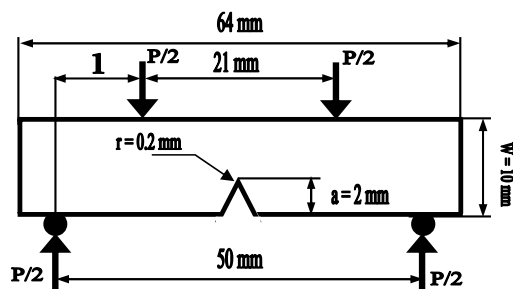


Fig. 2. V-notch specimen in four points bending test

## 2.2. Fatigue crack growth measurement

Fatigue crack growth tests were performed using closed-loop servo-hydraulic testing machine “INSTRON 8500 Digital Control” with 250 KN load capacity under applied constant amplitude sinusoidal wave loading at the frequency of 10 Hz and  $R=0.1$ . Specimens are subjected to the bending fatigue tested used by many researcher [13–15]. Stress intensity factor for V-notch bent specimen is expressed by the following expression [16]:

$$K=3Plf(a/w)/bw^2 \quad (1)$$

where  $f(a/w)$  is the geometry function given by:

$$f(a/w)=1.122-1.4(a/w)+7.33(a/w)^2-13.08(a/w)^3+14(a/w)^4 \quad (2)$$

In fatigue tests, we note the length of the crack (mm) versus number of cycles  $N$  ( $a=f(N)$ ). Secant method was used for modeling fatigue crack growth rates. The calculation is done using two pairs of adjacent measures ( $a_i$ ,  $N_i$ ) and ( $a_{i+1}$ ,  $N_{i+1}$ ). The rate of cracking at the point  $a_{i(moy)}$  is given by:

$$da/dN = (a_{i+1}-a_i)/(N_{i+1}-N_i) \quad (3)$$

## 3. Results & Discussions

The cracking at constant amplitude has undergone several tests for load ratio  $R=0.1$  at a frequency of 10 Hz Table 3 gives lifetimes (number of cycles) corresponding to a crack length between an initial value “ $a_0$ ” and a final value “ $a_f$ ” for different loading levels and same load ratio. Also the initial and final values of stress intensity factor are given.

Table 3: Fatigue life for different amplitude loading at  $R = 0.1$

Specimen	$a_0$ (mm)	$a_f$ (mm)	$P_{min}$ (KN)	$P_{max}$ (KN)	$\Delta P$ (KN)	$N$ (cycles)	$\Delta K_0$ $MPa\sqrt{m}$	$\Delta K_f$ $MPa\sqrt{m}$
01	3.965	6.515	0.191	1.913	1.917	163 530	13.14	26.56
02	3.40	7.87	0.114	1.145	1.031	455 628	5.473	25.06
03	3.21	7.415	0.128	1.285	1.157	194 500	5.85	23.15

In order to show the effects of amplitude loading, fatigue life curves are plotted according to crack length. Fig. 3 gives a curve  $a = f(N)$  for two tests at  $R = 0.1$  when  $P_{max}$  equal to 1.285 KN and 1.145 KN. We note that at fixed load ratio  $R$ , the fatigue life is affected by amplitude loading. Evolutions of fatigue crack growth rates ( $da/dN$ ) function of amplitude of stress intensity factor are plotted in Fig. 4. The solid lines represent the approximation by Paris Law. The parameters of the Paris law (see equation 4) [17] are affected load level (Table 4).

$$da/dN = C.\Delta K^m \quad (4)$$

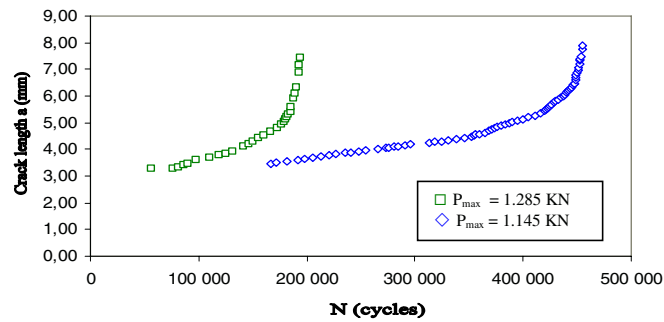
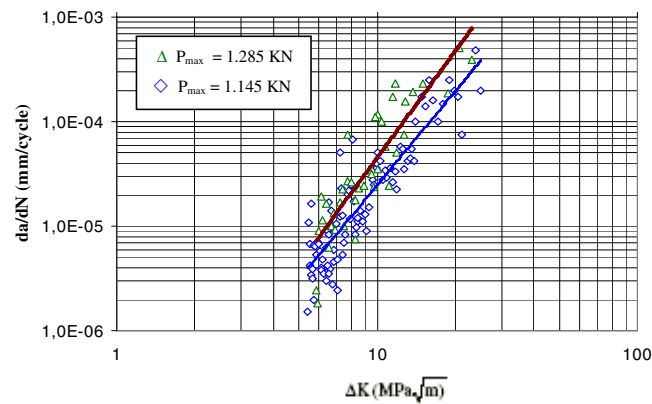


Fig. 3. Fatigue crack length as function of level of applied load

Table 4. Coefficients of Paris law (da/dN in mm/cycles)

Specimen	C	m
02	$2.1 \times 10^{-8}$	2.997
03	$2.0 \times 10^{-8}$	3.40

Fig. 4. Effect of level of amplitude loading on fatigue crack growth rate at  $R = 0.1$ 

To analyse the obtained results, we show that the amplitude loading affect considerable the parameter “m” of Paris law comparatively to the parameter “C”. In Fatigue crack growth curves, an increasing of the level of applied load (amplitude of loading) increase the fatigue crack growth rates. This effect is reflected by the effect of mean stress. The mean stress effect will be also affected by the load ratio. The results presented in Table 5, shown the stress ratio and amplitude loading effects on fatigue life and final crack length.

Table 5: Fatigue life under stress ratio effect

R	$a_0$ (mm)	$a_f$ (mm)	$P_{min}$ (KN)	$P_{max}$ (KN)	$\Delta P$ (KN)	N (cycles)	$\Delta K_0$ $MPa\sqrt{m}$	$\Delta K_f$ $MPa\sqrt{m}$
0.2	3.40	7.87	0.237	1.184	0.947	569 700	4.85	16.88
0.5	2.735	6.28	1.25	2.50	1.25	240 000	5.535	15.82

The fractographic examination of the fracture surfaces of aluminium alloy 2024 were carried out at the School of Mines of Paris (Centre of Materials: Pierre Marie Fournier, Evry) using a scanning electron microscope (SEM). This analysis enables to define microscopic fatigue crack growth rate by the measurement of the distances from fatigue striation spaces. Following the fractographic analysis of the fracture topographies, fatigue striations zone were localized. These surfaces enable us to determine the microscopic fatigue crack growth under the effect of levels of applied loading. Figs. 5 show the fracture surface of aluminum alloy under constant amplitude loading. Fig. 5 shown crystallographic fracture at low stress intensity factor with the presence of the secondary crack at boundaries grains. Fatigue striations for different load ratio ( $R=0.1$ ;  $0.2$ ;  $0.5$ ) are presented in Figs. 6, 7 and 8. We shown that at the same crack length, the fatigue crack growth rate is affected by load ratio and amplitude of loading.

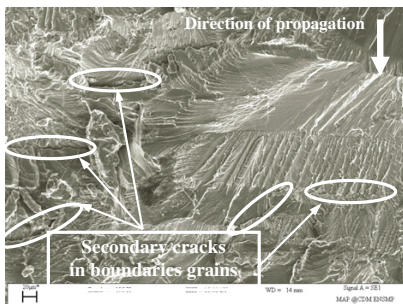


Fig. 5. Surface fracture for Al 2024 T351  
( $a = 2.5$  mm,  $\Delta K = 9.40$   $MPa\sqrt{m}$ )

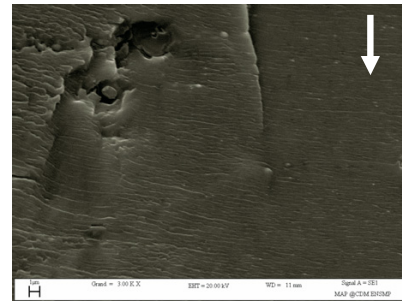


Fig. 6. Fatigue Striation at  $R=0.1$   
( $a=5.95$ ,  $\Delta K=10.74$   $MPa\sqrt{m}$ ,  $da/dN=4.28 \times 10^{-4}$  mm/cycle)

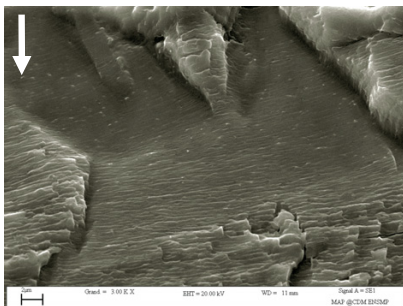


Fig. 7. Fatigue Striation at  $R=0.2$   
( $a = 5.89$  mm,  $\Delta K = 10.43$   $MPa\sqrt{m}$ ,  $da/dN = 4.00 \times 10^{-4}$  mm/cycle)

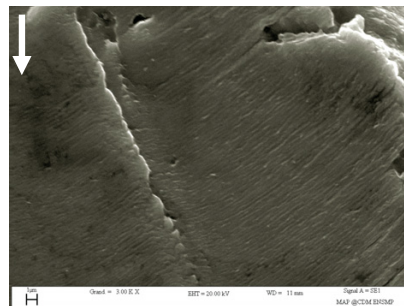


Fig. 8. Fatigue Striation at  $R=0.5$   
( $a=5.81$  mm,  $\Delta K=13.05$   $MPa\sqrt{m}$ ,  $da/dN=1.25 \times 10^{-3}$  mm/cycle)

#### 4. Conclusion

This paper reveals that under constant amplitude loading, the fatigue crack growth and the fatigue life are affected by amplitude or level of applied load. Results of FCGR characterized by Paris law shown that the parameters of the Paris model are affected by increasing the level of applied load. Stress ratio characterized by mean stress is an others extrinsic parameter who affect the fatigue behaviour. For the same stress ratio, an increasing of amplitude loading decreases the fatigue life and increase the FCGR. The examination of fracture surface reveals the presence of fatigue striations and the presence of secondary crack at boundary grains. The spacing striation was affected by stress ratio.

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